Maximizing Energy Efficiency and Minimizing Environmental Emissions in the Process Industry Using Thermal Pinch Analysis

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Efforts to increase plant energy efficiency intensify with the continuing increase in fuel prices and the growing global concern for environmental emissions. As new processes and technologies emerge, existing procedures are pressured to increase efficiency and maintain profitability to remain competitive. Many installations have focused on energy efficiency upgrading to increase profitability. Energy efficiency measures employed in local industries, however, have been generally confined to good housekeeping techniques and the upgrade of utility systems, such as boilers, steam systems, chillers, hot oil circuit, and refrigeration and cooling systems. Very few companies are willing venture into process operations to further reduce their energy consumption. As a result, the benefits that can be derived from retrofit projects have been greatly limited. The advent of thermal pinch analysis provides a comprehensive and systematic approach to maximize plant energy efficiency. This paper highlights some key features of thermal pinch analysis aimed at maximizing energy efficiency and reducing environmental emissions. It begins by describing the significance of pinch design targets and the use of simple graphical tools as guides for process modifications to reduce further energy usage and emissions. Finally, the paper highlights how the interactions between process plant and utility systems can be exploited to a company's advantage.

Keywords: Composite curves, grand composite curve (GCC), heat exchanger network synthesis (HENS), pinch technology, process design, thermal pinch analysis, true baseline target, *and* retrofit.

INTRODUCTION

The rapid growth of Malaysia's industrial sector over the last decade has resulted in an overall increase in energy demand. At the present rate of consumption, the nation's current conventional energy reserves would not last more than three decades (Sidhu 2003).

Increased fuel consumption has caused an unprecedented level of environmental pollution. The industry sector tops the country's list of major energy consumers with a total consumption of approximately 42%, followed by the transport sector with 39%, the residential sector with 13%, and the commercial sector with 6% (Velumail 2001). Thus, there is the pressing need to conserve energy by properly managing available resources. In general, the driving force behind energy efficiency is to save money. In the long-term, saving energy retards the depletion of nonrenewable energy resources and reduces environmental emissions.

Finding a cost-effective way to reduce environmental emissions remains one of the major challenges to the industrialized world. The widespread resistance to change in this direction, however, is not so much due to the plant managers and operators' lack of concern for environmental issues but to their perception that significant additional investment is invariably needed for a plant to reduce its emissions. In Europe and North America, stringent emission standards have resulted in the closure of some plants, while others have to operate with a shrinking profit margin. In developing countries where industrialization is fast gaining ground, similar changes are imminent. Since sound waste management has become a criterion for quality, it will not take long before the trend towards stringent environmental standards become global. To stay competitive means to resort to cleaner production and to abide by international environmental guidelines.

The advent of thermal pinch analysis offers a proactive as well as cost-effective option towards better resource and environmental management. It is evident that the more fuel is burned the more gaseous emissions will be produced. Thus, a process that uses energy more efficiently tends to be the less polluting option. Pinch analysis techniques have enabled many companies in Europe and America to prevail over others. The experience of multinational petrochemical corporations, such as Shell, Exxon, BP, Dow, Mitsubishi, JGC, and Union Carbide in Europe, the United States, and Japan have shown that pinch analysis has led to energy savings of 15–90% and capital savings of up to 30% (Linhoff et al. 1986). Developments in the application of water pinch analysis have led to water savings of 15–25% from simple piping and control changes. However, improvements related to process modifications and selective wastewater regeneration show greater savings, often exceeding 50% (Linhoff et al. 1998). It is clear that the application of pinch analysis techniques can help a company achieve significant reductions in energy usage as well as in effluent emissions, thereby reducing the burden of implementing expensive cleanup technologies.

This paper highlights the key features of thermal pinch analysis that have been aimed at maximizing energy efficiency and reducing environmental emissions. The paper begins by describing the significance of pinch design targets. It then explains how simple graphical tools can be used as guides for basic process modifications to reduce further energy usage and emissions. Finally, the paper underscores how interactions between the process plant and its effluent treatment systems can be exploited to the company's advantage.

USING THE TRUE BASELINE TARGET TO GUIDE DESIGN IMPROVEMENT

In general, it is easy to identify potential design improvements on existing plants and utility systems that can yield good payback. However, it is difficult to ascertain if a solution is the best for a given process. Often, a technologist working

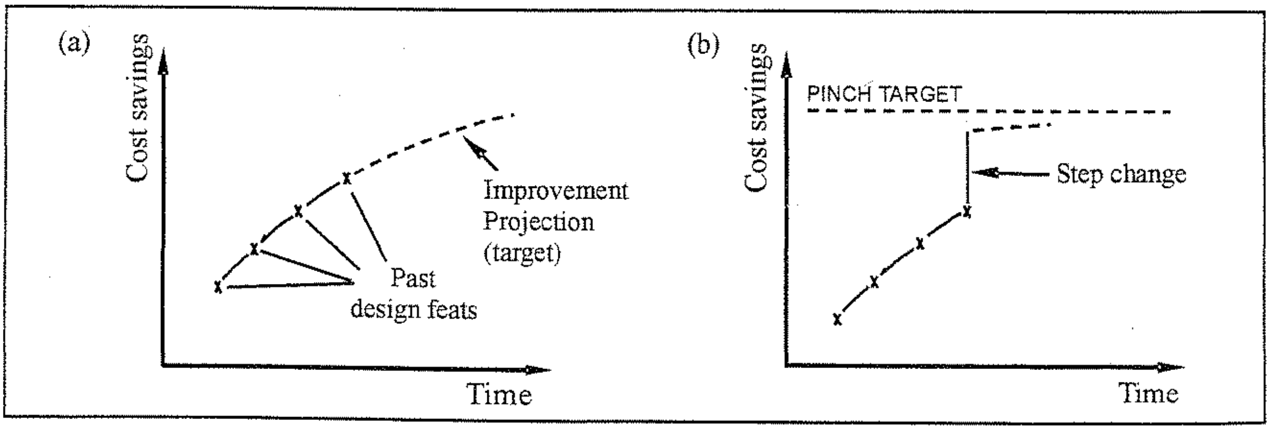

Figure 1. Guided by the pinch target, a "step change" in improvement can be achieved. This change may be a design based on (a) past performance (apparent baseline target) or (b) the pinch target (true baseline target).

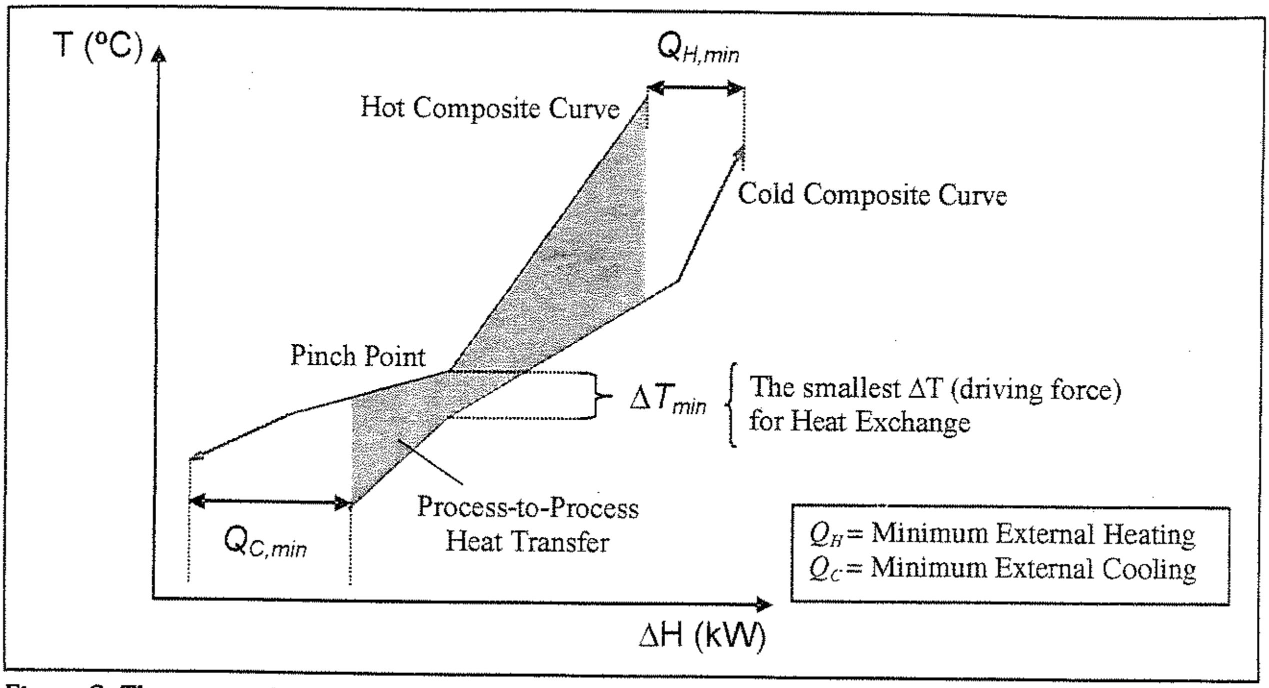

Figure 2. The composite curves represent the overall process heat availability and requirement as well as the energy targets.

on an improvement project is left with a nagging doubt: "Can I do better?" Even until today, progress made in process design has largely been based on a *learning curve* as shown in Figure 1a. A technologist would use a previous design feat, such as the specific energy consumption of a similar plant, for its benchmark. Such a benchmark, on the one hand, is referred to as an *apparent baseline target* since any improvement is only relative to a previous design feat. A *true baseline target*, on the other hand, is a benchmark based on the specific structure, operating conditions, and thermodynamics of the plant being built or being retrofit and not on the performance of a similar plant.

It is in terms of the true baseline target where thermal pinch analysis has a major advantage. Pinch applications begin with the setting up of the true baseline targets based on the thermodynamics of the process under study. The *true minimum energy targets* for a given section of a plant can be obtained from a plot of the *enthalpy* (energy) *aggregate* for the hot and cold streams of a process on a temperature vs. enthalpy diagram, such as the one shown in Figure 2. The pair of composite curves represents the overall process heat availability and requirement. The shaded region on the plot, where the hot and cold composites overlap, indicates the *maximum possible heat recovery* from the process streams. The overshoots of both the hot curves and the cold curves represent the *minimum hot and cold utility requirements,* or the energy targets for the process. The point of closest approach between hot and cold composites is referred to as the *pinch* that limits process heat recovery.

The *pinch* divides a process into two thermodynamically separate systems, each of which is in enthalpy balance with its relevant utility. It follows then that the hot utility (e.g., steam heating) is the only required utility for the process *above* the pinch. Likewise, only the cold utility (e.g., cooling water) is required *below* the pinch. In order to avoid excess utility consumption, three fundamental rules must be observed during the design and retrofit of processes:

1. Keep the systems above and below the pinch independent of one another. Never allow heat to be transferred across the pinch.
2. Below the pinch, only cold utility is needed. Therefore, hot utility is irrelevant.
3. Above the pinch, only hot utility is needed. Therefore, cold utility is irrelevant.

The *composite curves* provide profound insights on the design and retrofit of thermodynamically efficient systems. They have been proven useful in (a) representing the overall process streams heat quality and quantity, (b) generating the true baseline energy targets, and (c) assessing process inefficiencies. With the notion of true baseline design targets made available through pinch analysis, a technologist would less likely settle for marginal improvement and would strive to achieve the true baseline and, hence, the step-change in improvement as can be seen in Figure 1b. The technologist is also able to screen promising projects from marginal projects and assess if further improvement is worthwhile by simply comparing the performance gap between an existing design and the true baseline target.

USING PINCH RULES TO IDENTIFY PROCESS LOSSES

It can be said that one of the most important activities in the *heat exchanger network synthesis* (HENS) is retrofit as opposed to grassroots design. This is due to the fact that most process plants will undergo at least one major revamp in their plant lifetime to take advantage of process technology to improve energy efficiency or to increase the plant's throughput. For existing plants, three common types of *heat recovery network inefficiencies* may occur. These inefficiencies are in turn due to three types of key faults in the process *flowsheeting*, namely:

1. Hot utility supplied at the cold end (i.e., lower-temperature part) of a process (*heating below the pinch*);
2. Cold utility supplied at the hot end (i.e., higher-temperature part) of a process (*cooling above the pinch*); and,
3. Heat exchange mismatch between process streams (*cross-pinch heat transfer*).

Figures 3a and 3b represent a section of a palm oil refinery being retrofit. Figure 3a shows that *refined, bleached, and deodorized palm oil* (RBDPO) at 160°C and *steam heater* (H1) is used to heat the *crude palm oil feed* (CPO) at the cold end of the process. Another steam heater (H2) is used to heat the degassed oil from 104°C to 124°C. A careful observation of the stream conditions reveals that all three types of inefficiencies mentioned above exist in the refinery.

Note that there is a heat exchange mismatch between the RBDPO and the CPO streams. This mismatch occurs due to the use of high-temperature RBDPO to heat the CPO feed which is one of the streams with the lowest temperatures in the process. This heat exchange match prematurely brings down the temperature of the RBDPO to 95°C, thereby degrading the potential for the RBDPO to supply heat to streams at temperatures higher than 95°C, for example, to the degassed oil. The mismatch ultimately results in loss of the bulk of available heat in the RBDPO and the need for heater H1 to raise the CPO feed temperature to 97°C. The mismatch is a manifestation of *cross-pinch heat transfer* (type-3 fault). Meanwhile, H1 amounts to heating below the pinch (type-1 fault). Retrofit by rerouting the RBDPO to enable heat exchange between the RBDPO and the degasser exit stream prior to using the RBDPO for the CPO feed preheating would save the heat duty not only for heater H2 but also for H1. This has been made possible simply through better *process flowsheeting*, or the proper matching of process streams.

Figure 3b shows heat being rejected from an apparently valuable heat source, the bleacher exit at 120°C, directly into the cooling water via cooler C1. The exchange is a manifestation of type-2 fault, cooling above the pinch. This fault degrades the potential for the bleacher exit to supply heat to other process streams. The fault results in (a) loss of valuable heat source and (b) unnecessary use of cooling water. Note that these three faults can cost the plant dearly in terms of fuel, water bills, and extra gaseous emissions due to inefficient fuel consumption.

Detailed HEN retrofit performed by Manan et al. (2003) has shown that a maximum savings of 66% steam and 48% cooling water are possible with a projected payback period on investment of less than five months. Pinch retrofit procedures (Tjoe and Linnhoff 1986, Lim 2002) enable the cross-pinch matches to be detected and corrected to eliminate extra utility consumption and, hence, reduce emissions.

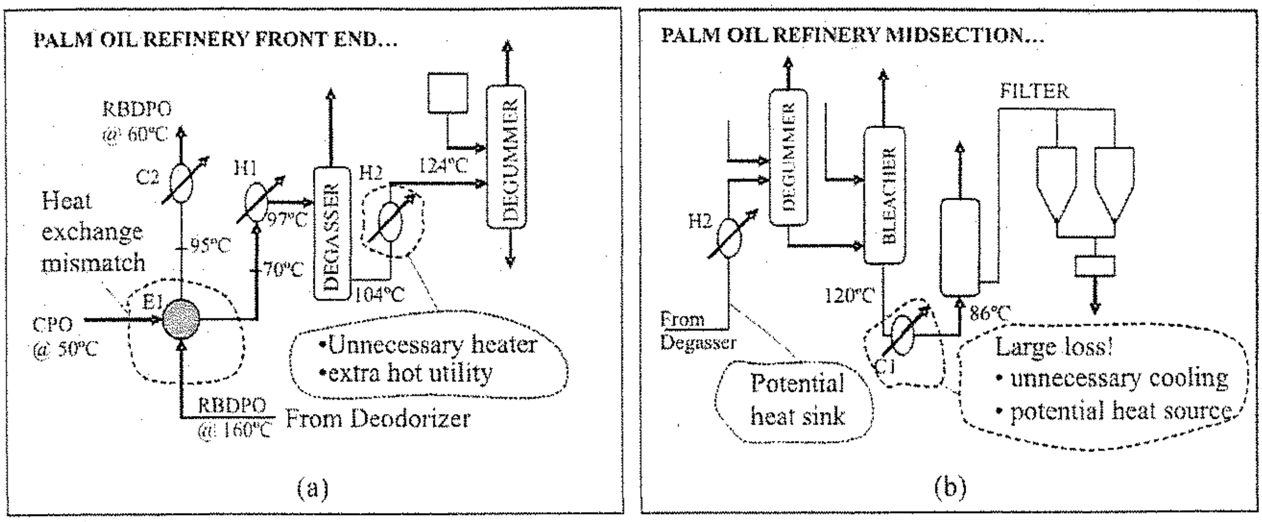

Figure 3. Two Key Faults in Process Flowsheeting: (a) Heating Below the Pinch and Cross-Pinch Heat Transfer and (b) Cooling Above the Pinch

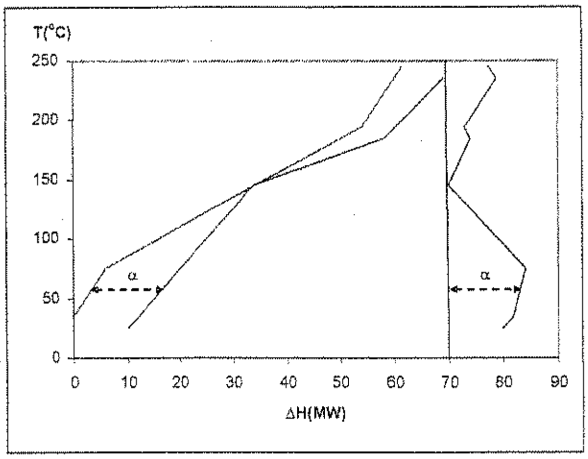

Figure 4. Construction of the GCC

THE GRAND COMPOSITE CURVE AND PROCESS MODIFICATIONS

The composite curves, however, give no clear indication of the appropriate utility level(s), especially in cases when several levels are employed. For this purpose, a knowledge of the different levels of process sources and sinks is needed.

The *grand composite curve*, or GCC, in figures 4 and 5 is a profile of the process sources and sinks. The curves are generated by plotting the horizontal gap between the composite curves for a given ΔT_{min}. The GCC allows a technologist

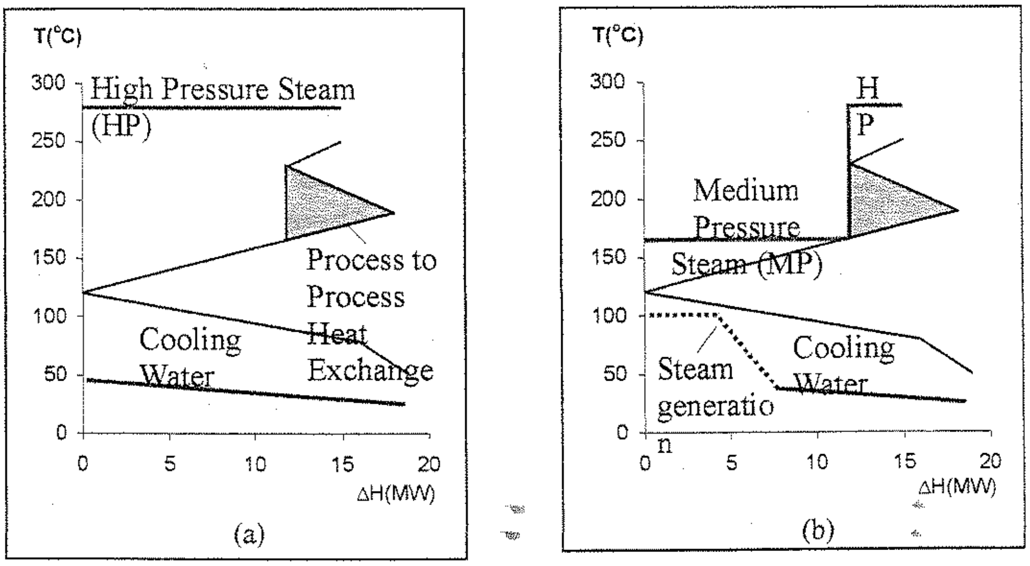

Figure 5. The grand composite curve provides an interface for the optimum selection of multiple utility levels: (a) one hot and one cold utility scenario and (b) multiple utilities.

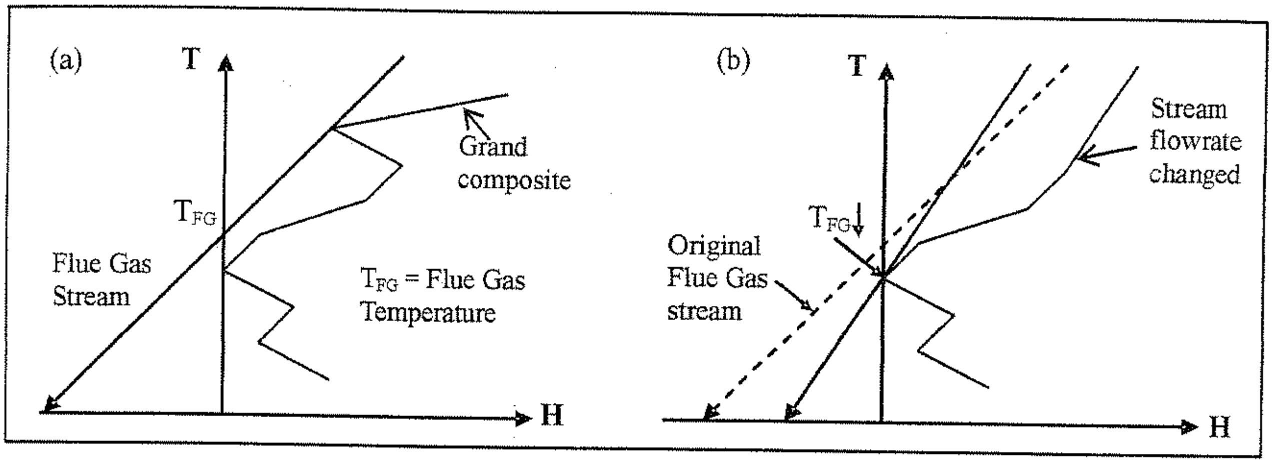

Figure 6. The GCCs help identify opportunities for process change. (a) The projecting part of the process GCC limits the flue gas line. (b) Changing the flowrate of a process stream allows a steeper flue gas line to be matched against the process, lower T_{FG}, and ultimately reduce fuel consumption with the improvement in furnace efficiency.

to select the most economic utility or utility combination for a process. It provides an interface for the selection of the optimum utility system.

The minimum energy targets generated from the enthalpy aggregate of the process streams are based on fixed equipment conditions. It is possible to reduce these targets by optimizing equipment conditions. For reactors and separators, some of the possible parameteric changes that could lead to the reduction of energy targets and, hence, emissions, include: reactor conversion and recycle flowrate, distillation reflux ratio, column pressure, pump around flowrate, and column feed preheat.

Opportunities for process changes can be conveniently identified and systematically performed using the process GCCs as illustrated in the following examples. The GCCs in figures 6a and 6b represent the high temperature part of a process heated by a furnace flue gas stream (Smith and Petela 1990a). The steepest flue gas line that can be drawn against the existing process is shown in Figure 6a. This line represents the smallest flue gas flowrate corresponding to the lowest fuel consumption.

"Trimming" the projecting part of the GCC by changing the stream flowrate which forms the projecting part of the curve will allow a steeper flue gas line to be matched against the process. The steeper flue gas line results in reduced fuel consumption due to reduced ambient losses. Note that, in this case, the overall process heating requirement remains unchanged.

UTILITY SYSTEM RETROFIT

Utility system is designed based on the heating and cooling needs of a plant. These needs depend on how well equipment such as reactors, separators, and heat recovery networks, are designed. Novel equipment designs will naturally result in lower utility requirements. So, the best strategy to achieve worthwhile reduction on an existing plant's utility requirement is to start at the "root" of the problem, which is the reactor. This should be followed by a retrofit of the separator, recycle system, and heat recovery network. By observing this hierarchy of process improvement, the true energy needs of a plant will be established.

Once the reactor, separator, recycle system, and heat recovery network have been examined, the next step is to assess the scope of improving the utility system. It is important to check if a utility line has been properly matched against a process. For example, it may be possible to supply utilities at lower pressures (in the case of steam) or higher temperatures (in the case of refrigerant) in order to save cost. Opportunities for installing a heat-and-power scheme can be considered if the retrofit steam

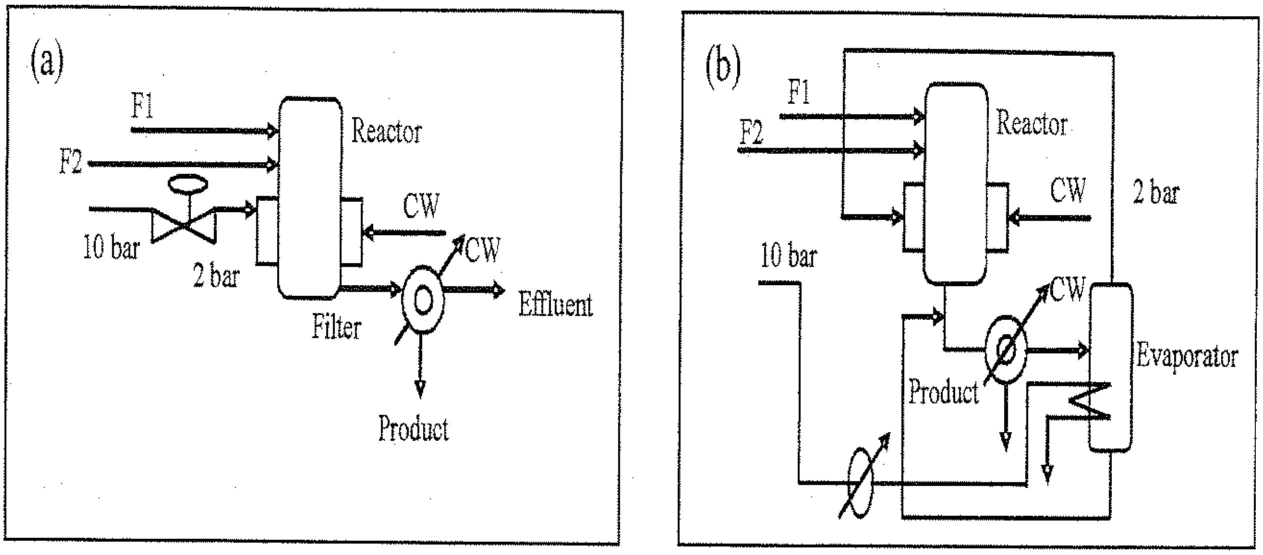

Figure 7. (a) A specialty chemical process before retrofit, with steam being throttled from 10 bar to 2 bar. (b) The medium pressure steam at 10 bar is used for further product recovery thereby avoiding throttling losses. The vapor from the evaporator is used for reactor heating (Tjoe and Linhoff 1986).

pressure is much lower than that before the retrofit. Likewise, power pconsumption can be reduced if the use of low temperature refrigerant can be minimized or avoided. All of these potential improvements can be quickly explored through the GCC.

There are cases where utilities are employed at qualities significantly higher than what are required by a plant. Steam supplied at a pressure higher than the utilization pressure is normally throttled down to the desired pressure. Figure 7a shows a section of a specialty chemical manufacturing plant (Smith and Petela 1991–1992). The reactor requires only a 2-bar steam pressure for heating. Since the steam supply pressure is at 10 bar, it is throttled all the way down to 2 bar to meet the reactor's heating requirement.

Thus, there is the need to increase product recovery in the plant. In order to take advantage of the 10-bar medium pressure steam available, an evaporator has to be considered for the task. The proposed retrofit scheme is illustrated in Figure 7b. The scheme manages to increase product recovery while preventing steam "throttling losses."

Note that the energy cost has not increased; instead, raw materials and effluent treatment costs have been reduced through enhanced product recovery.

CONCLUSIONS

The best way to treat waste is to avoid its formation at the source. It is evident that the more fuel is burned the more gaseous emissions will be produced. Thus, a process that is efficient in its energy usage tends to be the less-polluting process.

Perhaps the most significant advantage in the application of pinch analysis techniques is the *true baseline target* made available in the form of the composite curves.

From these composite curves, on the one hand, three key pinch analysis rules emerge as practical tools to pinpoint process inefficiencies:

1. Keep the systems above and below the pinch independent of one another. Never allow heat to be transferred across the pinch.
2. Below the pinch, only cold utility is needed. Therefore, hot utility is irrelevant.
3. Above the pinch, only hot utility is needed. Therefore, cold utility is irrelevant.

The grand composite curve or GCC, on the other hand, is instrumental as a guide for utility optimization and basic process modifications to further reduce energy usage and emissions. The advent of thermal pinch analysis techniques not only enable technologists to maximize energy efficiency and reduce process emissions, but also to minimize the investment and operating costs needed by treatment plants.

REFERENCES

Lim, F. Y. (2002, September). "MATRIX—A new systematic technique for retrofit of heat exchanger network." MSc Thesis, Universiti Teknologi Malaysia.

Linnhoff, B. et al. (1986). *Process integration*, Monograph, ICI.

Linnhoff, B. et al. (1998, August 5). "Intelligent networking of process wastewater streams in the chemical industry," White Paper.

Manan, Z. A., Ooi, B. L., Lim, F. Y., and Foo, C. Y. (2003). "Heat-MATRIX—A computer software for the reduction of energy and water in process plants." 31st International Exhibition of Invention, New Techniques, and Products, Geneva, Switzerland.

Tjoe, T. N., and Linnhoff, B. (1986). "Using pinch technology for process retrofits," *Chem. Eng.*, *93*, 8, 47–60.

Sidhu, B. K. (2003). "Shell out for more" [Starbiz], *The Star*, 12–3.

Smith, R., and Petela, E. A. (1990). "Minimization of environmental emissions through improved process integration," *Heat Recovery Systems and CHP*, *10*, 4, 329–39.

Smith, R., and Petela, E. A. (1991). "Waste minimizations in the process industries: 1. The Problem," *Chem. Eng.*, *506*, 31.

Smith, R., and Petela, E. A. (1991). "Waste minimizations in the process industries: 2. Reactors," *Chem. Eng.*, *509/510*, 12.

Smith, R., and Petela, E. A. (1991). "Waste minimizations in the process industries: 3. Separation and Recycle Systems," *Chem. Eng.*, *513*, 13.

Smith, R., and Petela, E. A. (1992). "Waste minimizations in the process industries: 4. Process Operations," *Chem. Eng.*, *517*, 9.

Smith, R., and Petela, E. A. (1992). "Waste minimizations in the process industries: 5. Utility Waste," *Chem. Eng.*, *523*, 16.

Velumail, T. (2001, February 14–15). "Policy and initiatives on new and renewable energy in Malaysia." Conference on New and Renewable Energy Development and Utilisation for Global Environment Protection, Ministry of Energy, Communications and Multimedia, Kuala Lumpur, Malaysia.